Sterile Neutrinos: Global (Oscillation) Fits

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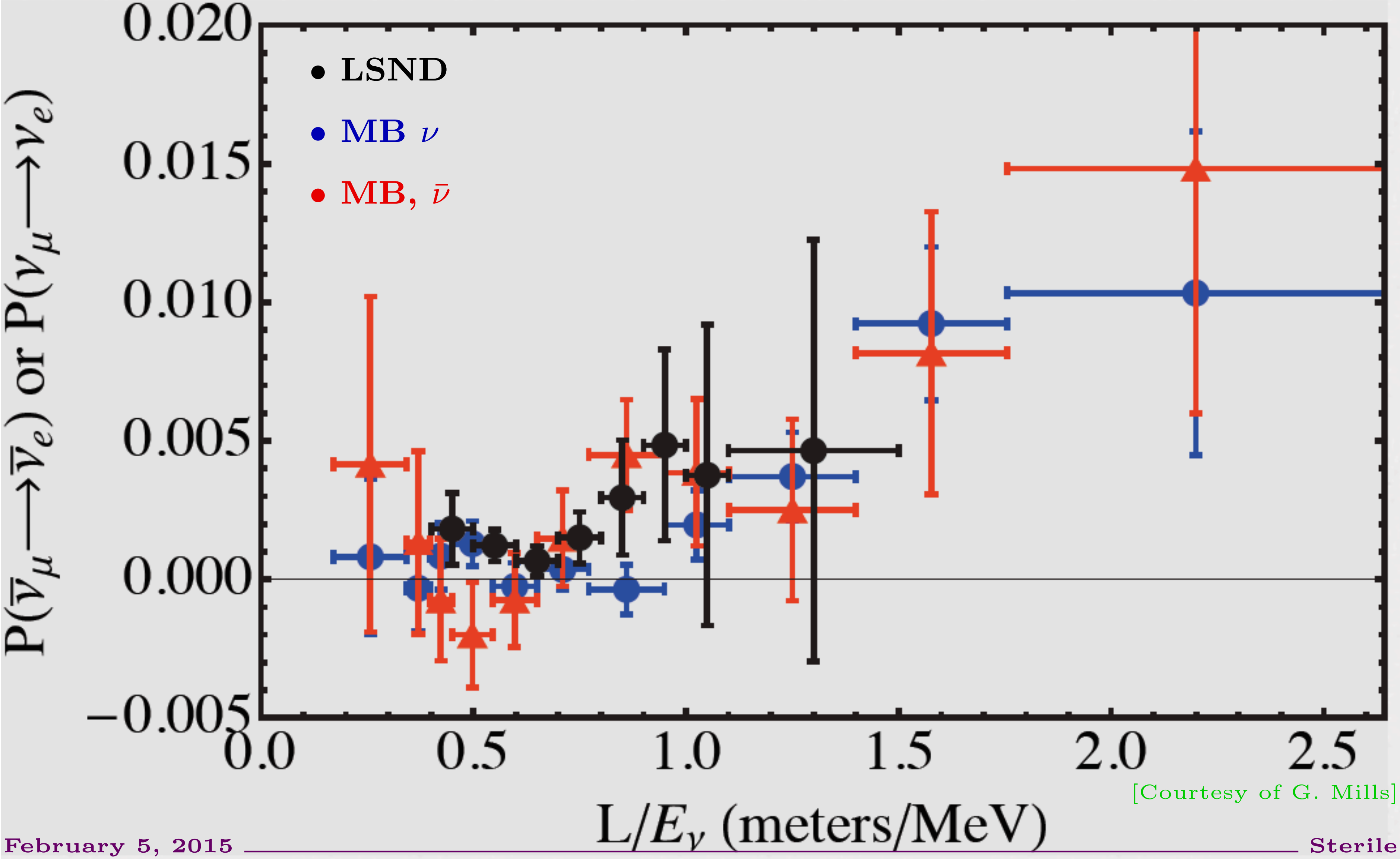
Not all is well: The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have "time" to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

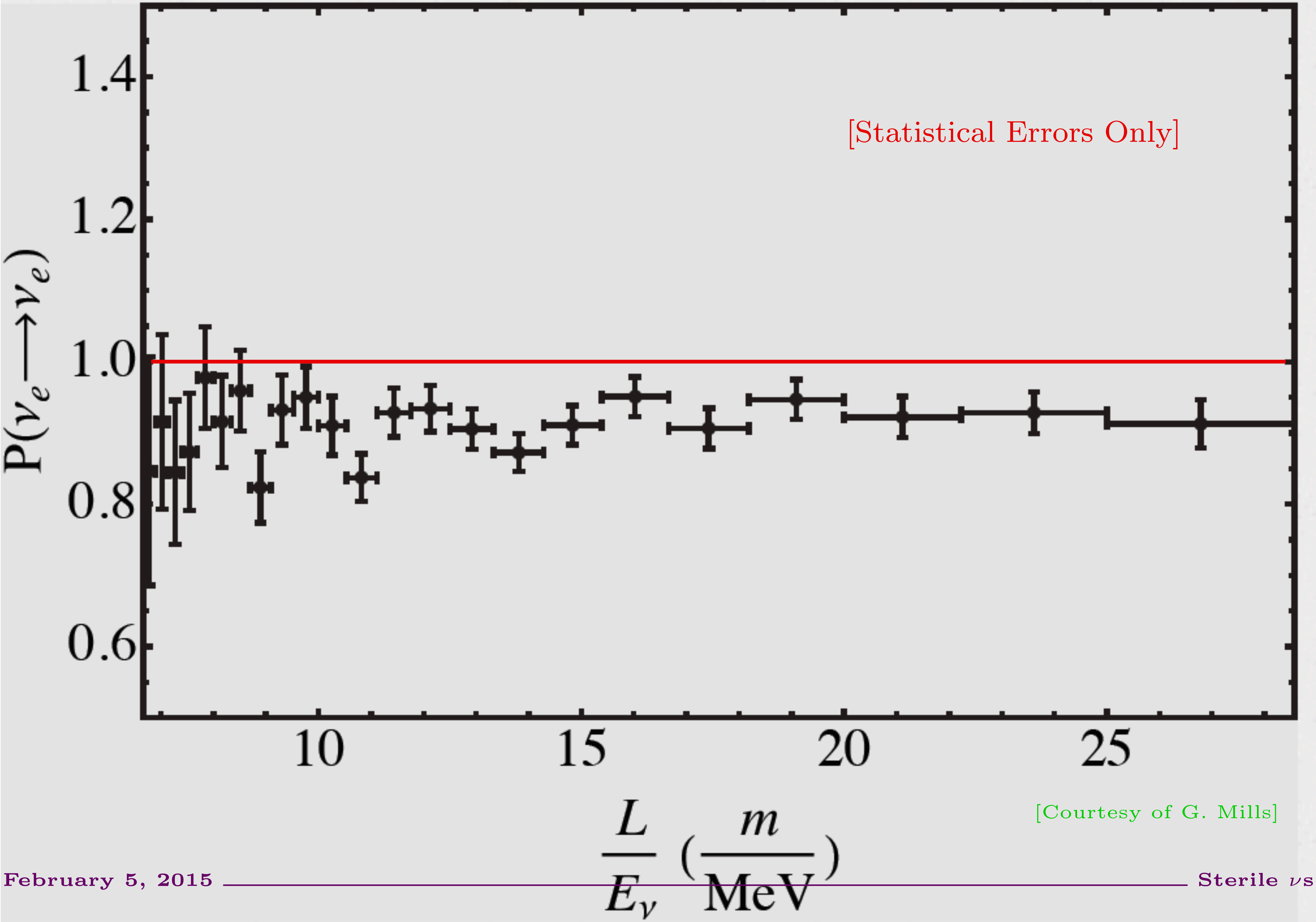
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



[Courtesy of G. Mills]

Bugey 40 m



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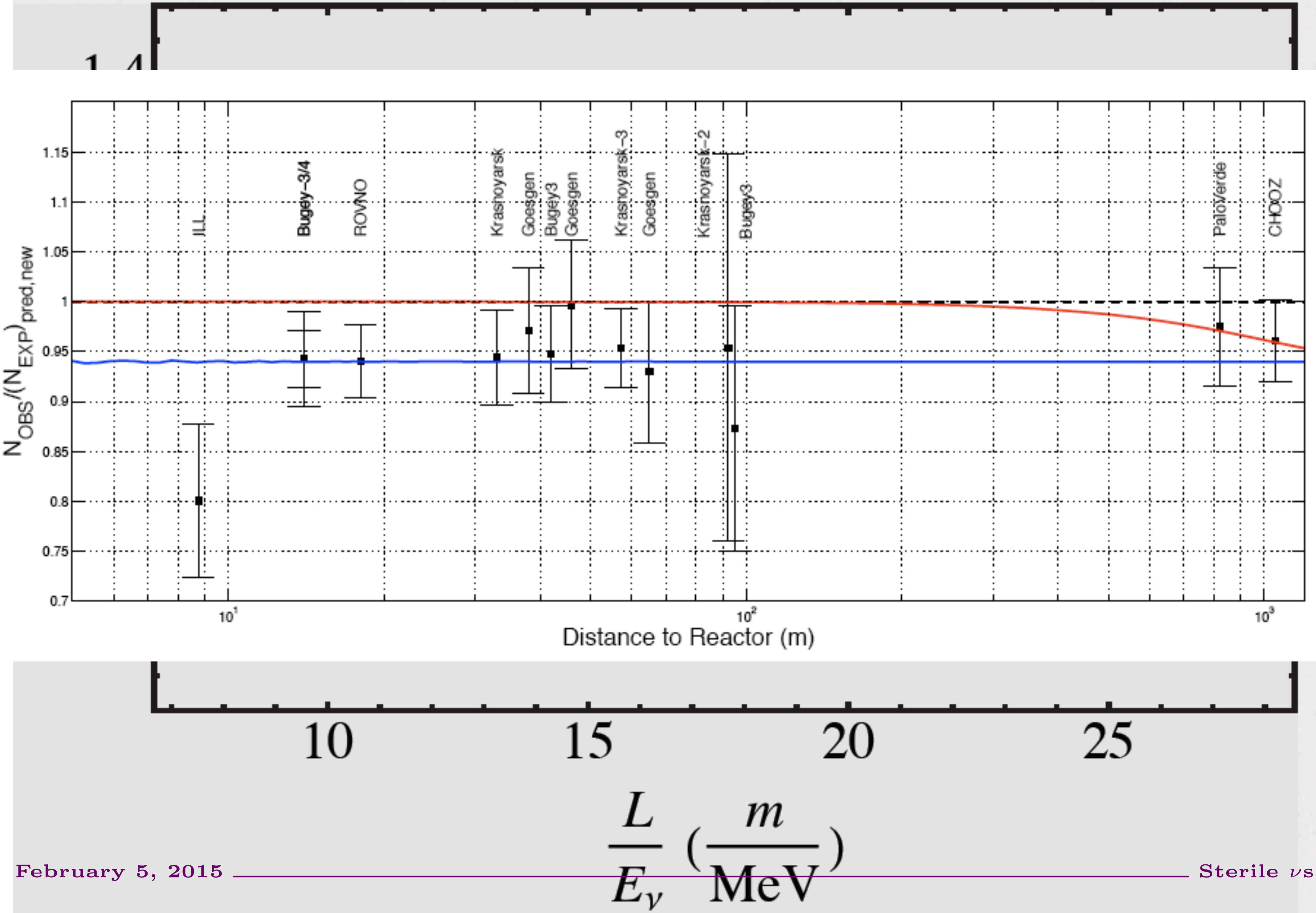
Bugey 40 m



ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ
$N_{OBS}/(N_{EXP})_{pred,new}$
Distance to Reactor (m)
10
15
20
25
$\frac{L}{E_\nu}$ $(\frac{m}{\text{MeV}})$

What is Going on Here?

- Are these "anomalies" related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type!

Observable wish list:

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \rightarrow \nu_\tau$ appearance.

A neutrino oscillation solution require new neutrino states ν_4, ν_5, etc with masses m_4, m_5, etc. Reason is simple: L/E too small (hence *Short Baseline Anomalies*).

The probability that ν_4 is measured as a ν_e is U_{e4}, the probability that ν_5 is measured as a ν_μ is $U_{\mu 5}$, and so on.

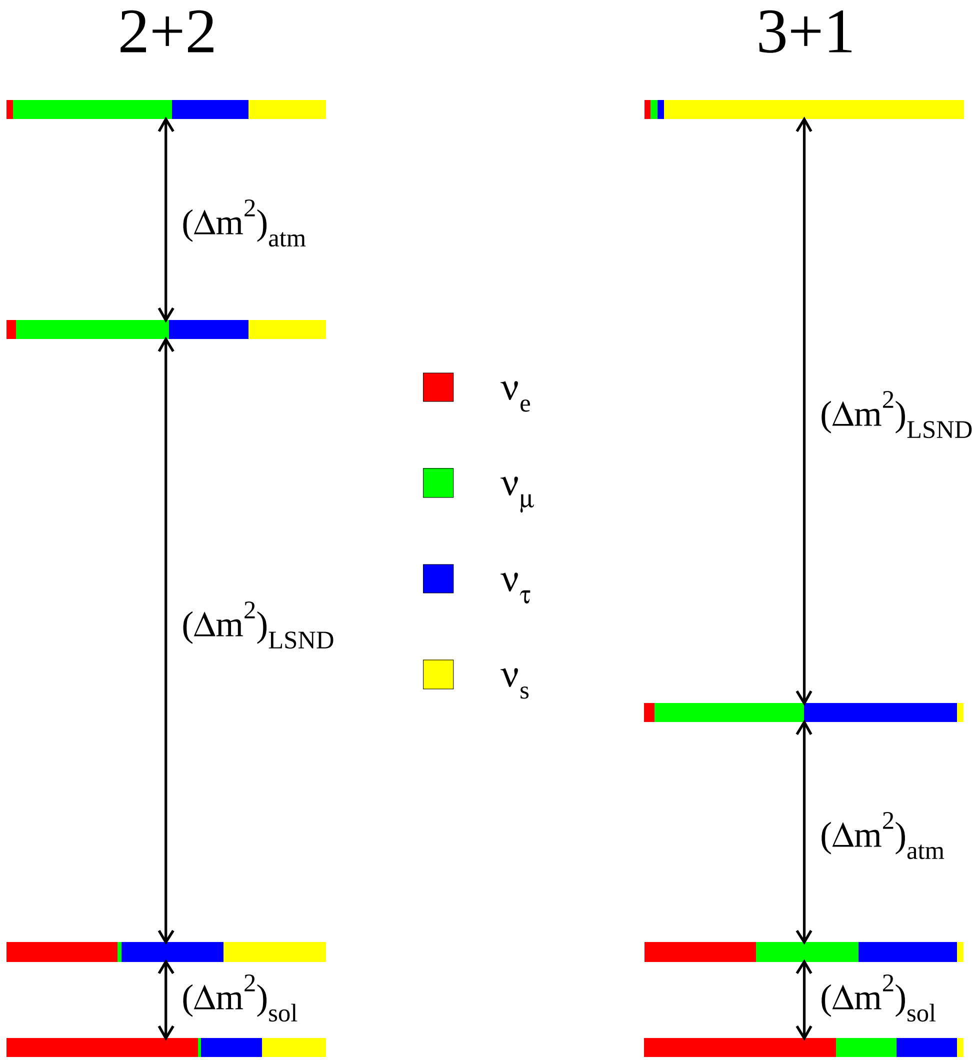
I will report on the recent global analyses of the relevant data, currently pursued by three groups:

- J. Conrad *et al*, arXiv:12074765;
- C. Giunti *et al*, arXiv:1308.5288;
- J. Kopp *et al*, arXiv:1303.3011.

The results of all three groups more or less agree. For concreteness I will show the results from arXiv:1303.3011.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s_1} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

[Parameterizing the matrix is interesting. See AdG, Jenkins, PRD78, 053003 (2008)]



$\Rightarrow$ 2+2 requires large sterile effects in either solar or atmospheric oscillations, not observed

Experiment	dof	channel	comments
Short-baseline reactors	76	$\bar{\nu}_e \to \bar{\nu}_e$	SBL
Long-baseline reactors	39	$\bar{\nu}_e \to \bar{\nu}_e$	LBL
KamLAND	17	$\bar{\nu}_e \to \bar{\nu}_e$	
Gallium	4	$\nu_e \to \nu_e$	SBL
Solar neutrinos	261	$\nu_e \to \nu_e$ + NC data	
LSND/KARMEN ^{12}C	32	$\nu_e \to \nu_e$	SBL
CDHS	15	$\nu_\mu \to \nu_\mu$	SBL
MiniBooNE ν	15	$\nu_\mu \to \nu_\mu$	SBL
MiniBooNE $\bar{\nu}$	42	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	SBL
MINOS CC	20	$\nu_\mu \to \nu_\mu$	LBL
MINOS NC	20	$\nu_\mu \to \nu_s$	LBL
Atmospheric neutrinos	80	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ + NC matter effect	
LSND	11	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL
KARMEN	9	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL
NOMAD	1	$\nu_\mu \to \nu_e$	SBL
MiniBooNE ν	11	$\nu_\mu \to \nu_e$	SBL
MiniBooNE $\bar{\nu}$	11	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL
E776	24	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	SBL
ICARUS	1	$\nu_\mu \to \nu_e$	LBL
total	689		

Table 1. Summary of the data used in this work divided into $\overset{(-)}{\nu}_e$, $\overset{(-)}{\nu}_\mu$ disappearance, and appearance data. The column "dof" gives the number of data points used in our analysis minus the number of free nuisance parameters for each experiment.

J. Kopp *et al*, arXiv:1303.3011

Bottom line: Fits to *all data* are mediocre – no "feel good" solution! On the other hand, I think it is not correct to say the hypothesis is ruled out.

	$\chi^2_{\rm min}$/dof	GOF	$\chi^2_{\rm PG}$/dof	PG	$\chi^2_{\rm app,glob}$	$\Delta\chi^2_{\rm app}$	$\chi^2_{\rm dis,glob}$	$\Delta\chi^2_{\rm dis}$
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}	95.8/68	7.9	616/621	10.1
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}	92.4/68	19.7	609/621	6.1
1+3+1	694/(689 − 14)	30%	16.8/4	2.1×10^{-3}	82.4/68	7.8	611/621	9.0

Table 7. Global χ^2 minima, GOF values, and parameter goodness-of-fit (PG) test [125] for the consistency of appearance versus disappearance experiments in the 3+1, 3+2, and 1+3+1 schemes. The corresponding parameter values at the global best fit points are given in Tab. 8. The last four columns give the contributions of appearance and disappearance data to $\chi^2_{\rm PG}$, see Eq. (6.2).

J. Kopp *et al*, arXiv:1303.3011

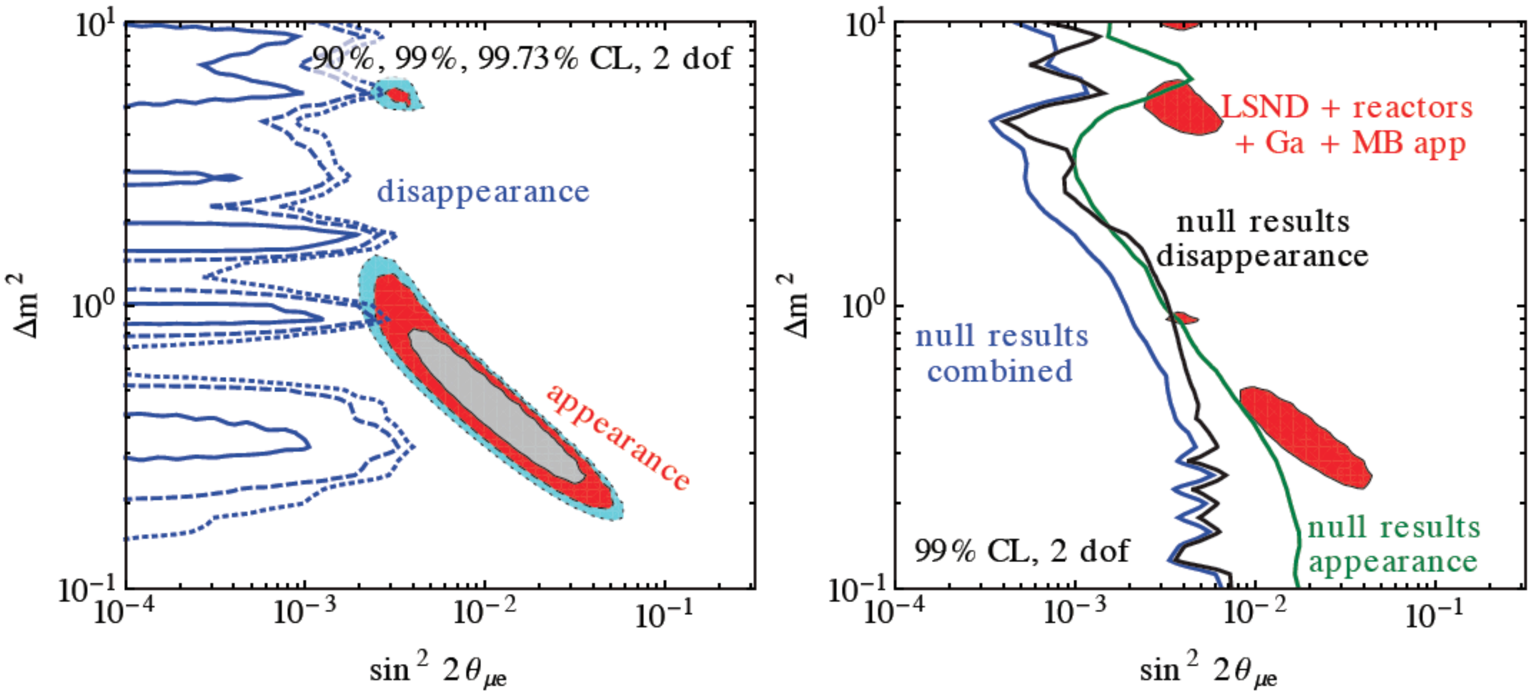
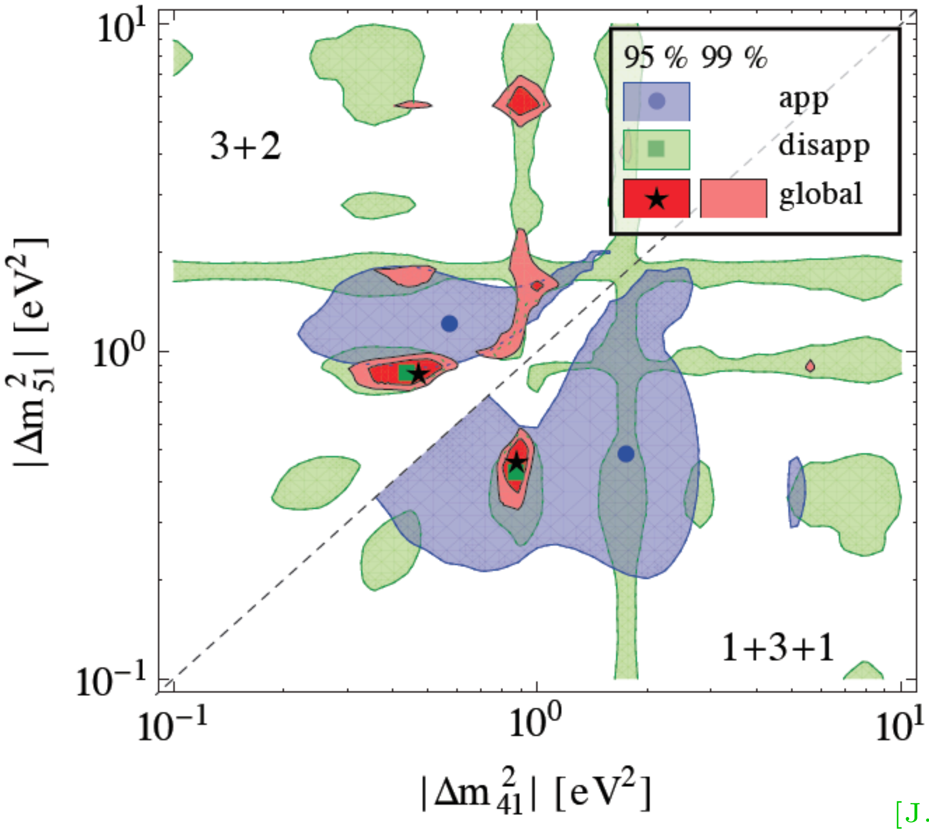


Figure 8. Results of the global fit in the 3+1 scenario, shown as exclusion limits and allowed regions for the effective mixing angle $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$ and the mass squared difference Δm^2_{41}. Left: Comparison of the parameter region preferred by appearance data (LSND, MiniBooNE appearance analysis, NOMAD, KARMEN, ICARUS, E776) to the exclusion limit from disappearance data (atmospheric, solar, reactors, Gallium, CDHS, MINOS, MiniBooNE disappearance, KARMEN and LSND ν_e–^{12}C scattering). Right: Regions preferred by experiments reporting a signal for sterile neutrinos (LSND, MiniBooNE, SBL reactors, Gallium) versus the constraints from all other data, shown separately for disappearance and appearance experiments, as well as their combination.

[J. Kopp *et al*, arXiv:1303.3011]

	Δm^2_{41} [eV^2]	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51} [eV^2]	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	$\gamma_{\mu e}$
3+1	0.93	0.15	0.17				
3+2	0.47	0.13	0.15	0.87	0.14	0.13	-0.15π
1+3+1	-0.87	0.15	0.13	0.47	0.13	0.17	0.06π

Table 8. Parameter values at the global best fit points for the 3+1, 3+2, and 1+3+1 mass schemes. $\gamma_{\mu e}$ is the complex phase relevant for SBL appearance experiments as defined in Eq. (2.2).



[J. Kopp *et al*, arXiv:1303.3011]

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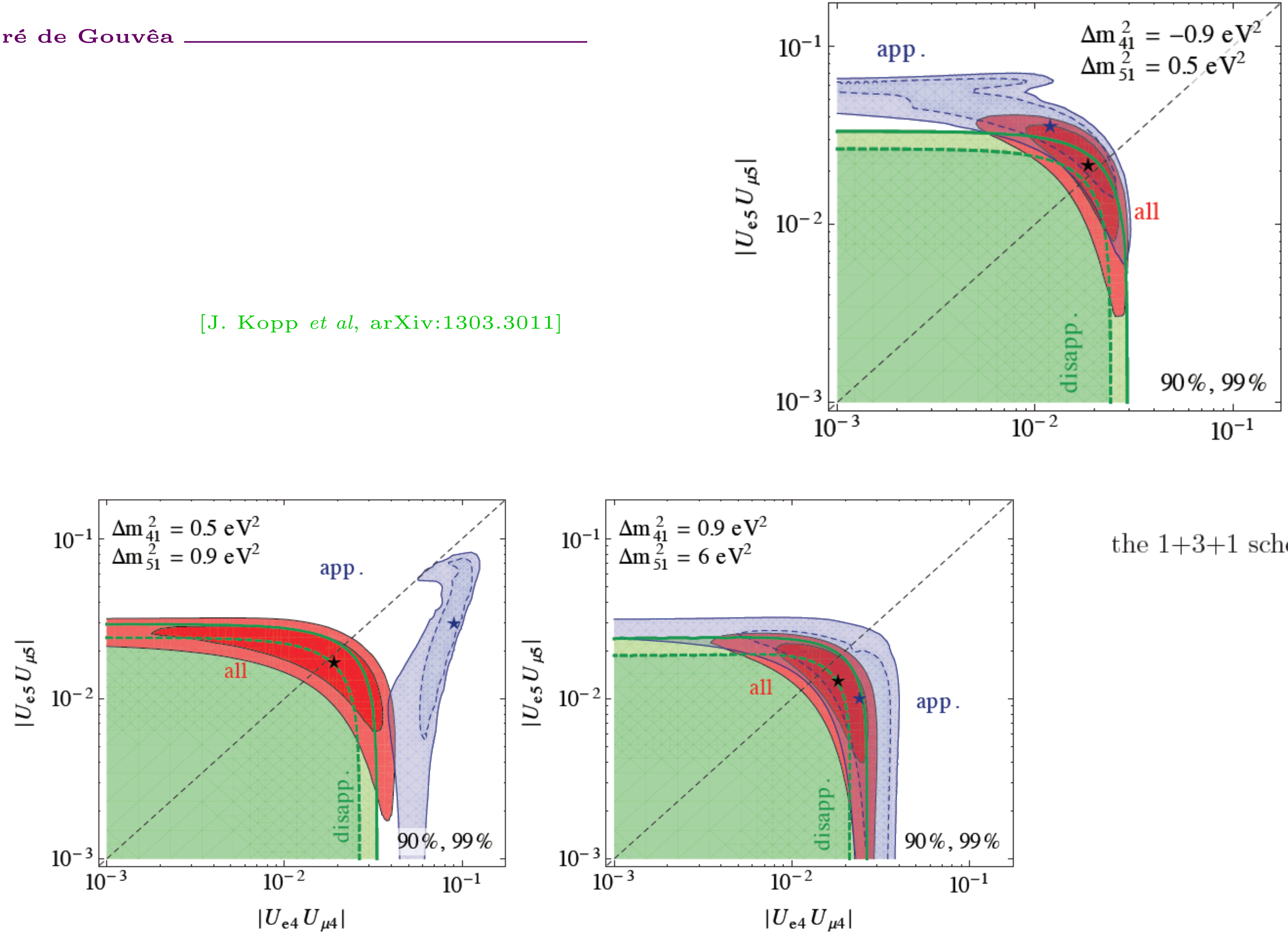

the 1+3+1 scheme.

Figure 10. Allowed regions for 3+2 in the plane of $|U_{e4}U_{\mu4}|$ vs. $|U_{e5}U_{\mu5}|$ for fixed values of Δm^2_{41} and Δm^2_{51} at 90% and 99% CL (2 dof). We minimize over all undisplayed mixing parameters. We show the regions for appearance data (blue), disappearance data (green), and the global data (red).

Parting Statements

1. The $3+N$ Light-Neutrinos hypothesis fits all data. The fit, however, is not great.

2. More work needed(?) Is the hypothesis allowed? At what Confidence level?

3. We definitely need more data!